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HEAVY OIL AS FUEL

FOR

INTERNAL-COMBUSTION ENGINES

BY

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HEAVY OIL AS FUEL FOR INTERNAL-COMBUSTION ENGINES.

By Irving C. Allen.

INTRODUCTION.

The many inquiries addressed to the Bureau of Mines regarding the supply of heavy oils and the use of these oils as fuel for steam raising and for internal-combustion engines have made the issue of this paper advisable. It presents the result of an extended search in the United States and abroad for some means of more effectively burning the heavy asphaltum oils of the Pacific and the Gulf coasts.

VARIETIES OF LIQUID FUEL.

GAS OIL.

On the Pacific and Gulf coasts of the United States, not to consider the increasing output in Mexico (1),[a] there is produced a great quantity of heavy asphaltum oils. These may be refined and first-class products manufactured therefrom. In this refining, as also in the refining of the petroleums from the other oil fields of the United States, there is produced a so-called gas oil, which is that portion of the petroleum distilling between the heavy naphthas or kerosenes and the light spindle oils. It is too heavy for lamp oils or for burning in a gasoline engine, and is too light for lubricants. The United States Geological Survey (2) states that there was produced in 1911 from the California and Gulf coast oil fields 101,381,285 barrels of crude petroleum, valued at $50,942,446. This petroleum on refining would have yielded approximately 5 per cent, or 5,069,064 barrels, of gas oil. From the other oil fields of the United States in 1911 there was produced 119,068,106 barrels of crude petroleum, valued at $83,102,306, of which approximately 3 per cent, or 3,572,043 barrels, was gas oil, making a total of 8,641,107 barrels of gas oil.

USE IN GAS MANUFACTURE AND AS STEAM FUEL.

This gas oil, as its name implies, can be cracked in hot retorts and an excellent illuminating gas made therefrom (3–8), or it may be burned with good results as a fuel under steam boilers.

[a] Figures in parentheses, as here, refer to publications correspondingly numbered in the accompanying bibliography.

USE IN EXPLOSION ENGINES.

By being mixed or blended with a small proportion of the low-boiling natural gasolines (9) gas oil can be enlivened, by increasing its volatility and lowering its specific gravity and flash point, and made to burn in explosion engines. Even with the above uses gas oil has been produced in greater quantities than can be efficiently consumed, and its profitable disposal has been a burden on the refiners. In the past few months, however, due to the enormous demand for gasoline, gas oil has been recracked in the stills at the refineries and a part converted into gasoline.

This led the Bureau of Mines to seek more efficient means for its use. The heavy-oil internal-combustion engine—that is, the various modifications of the Diesel type—seemed to open a promising field, and a critical study of these engines abroad and in the United States has developed very encouraging results. A study of the use of gas oil in this engine has naturally led to the study of other similar oils, and the fact has been developed that there is being produced in greater and greater quantities in the United States coal tars and tar oils from gas works and coke plants.

COAL TARS AND TAR OILS.

There were produced in the United States in 1909 (10) 60,126,006 gallons of coal tar, valued at $1,408,611, and 92,152,938 gallons of gas tars, valued at $1,875,549. The production has been materially increased since that time (11, 12).

LIGNITE TARS.

In the California, North Dakota, Oregon, and Texas fields (13) there was produced in 1910, 1,555,068 tons of lignite, valued at $2,907,977. In North Dakota, where lignite mining is best developed (14), considerable work has been done on the manufacture of gas and briquets from lignite. It seems, however, that little consideration has been given to the subject of tar and by-product manufacture. This should be given first consideration if one looks to the best conservation of the raw lignite.

These tar oils burn successfully in the heavy-oil engine, and are therefore an additional and very important source of power. The coal-tar and lignite industries have been developed to a high degree of efficiency in Europe (15–18), where they are decidedly profitable, and there is no reason why they should not be made profitable in the United States as well.

USE OF WOOD TARS AND TAR OILS.

In working up wood wastes, wood tars and tar oils that can be used in the heavy-oil engine are being produced by distillation in

increasing quantities. In 1909 there were produced in the United States (19) 361,221 gallons of wood oils and 1,364,984 gallons of tars, the total value of which was $177,833. The production must have been materially larger in 1912. The waste wood of our forests offers a profitable source for liquid fuels, and the demand for and the consequent production of other wood by-products, such as creosotes, alcohols, etc., will increase with the growth of these industries.

USE OF SEED OILS AND ANIMAL OILS.

The seed and animal oils can be used as liquid fuels in an emergency, burning well in heavy-oil engines, but because of their greater value for other uses in the industries they are not at present a factor as liquid fuel.

USE OF ALCOHOLS.

The alcohols burn successfully in heavy-oil engines when mixed in the proportion of 80 parts of alcohol with 20 parts of benzene. The wood alcohols, by-products of destructive distillation of waste woods, and also alcohols prepared as products of fermentation from grains and other carbonaceous materials (20–22), as waste cornstalks, grain stalks, etc., offer a most promising field as a source of fuel for these engines whenever such products from these waste materials are produced in greater quantities than can be economically used in other ways, and when in an emergency a demand for liquid fuel becomes imperative.

OUTLOOK FOR SUITABLE FUEL.

These great sources of liquid fuels open practically an unlimited supply for heavy-oil engines, and the future for these engines in this country is very promising. It would be to our material advantage (23) to manufacture from our bituminous coals, woods, and oil residues the gases, tars, cokes, and the many other by-products, and to use these in their proper places in the industries rather than to burn the crude materials wastefully, as at present, directly under steam boilers for power generation. This would not make oil a competitor to the disadvantage of coal (24), but would increase the usefulness of coal by developing its possible by-products and thereby increase the value of the raw coal itself.

As approximately 0.4 pound (25) of an oil similar to gas oil will produce 1 horsepower-hour when burned in a heavy-oil engine, the total production of gas oil from the petroleum fields for 1911 would alone, without considering the vast resources of coal and wood oils, develop approximately 6,351,213,645 horsepower-hours without in any way interfering with the uses of the other petroleum products now manufactured. This would mean the addition of about 725,000 horsepower running continuously throughout the year.

THE HEAVY-OIL ENGINE.

The foregoing grouping of oils is intended to include those suitable for fuel in the various forms of engines developed from the Diesel engine. The particular features of this type of engine are briefly described for this paper by O. P. Hood, chief mechanical engineer of the Bureau of Mines, as follows:

Oil engines have been built, using the heat of combustion in several ways to develop power. The ordinary explosion type of engine, in which the combustion is completed in so short a time that practically no change in the cylinder volume takes place during combustion, employs a method of using heat much more efficient than the method available for a steam engine, yet far less efficient than is actually possible. In an attempt to realize in an engine the most favorable method of using heat, Dr. Rudolph Diesel, of Munich, proposed in 1893 what has proved to be, from a thermal standpoint, the most economical heat engine so far devised, and the one that most nearly approaches theoretical maximum efficiency. This engine is especially adapted to the burning of heavy oils. Its operation has two features that distinguish it especially from the explosion type of engine, which it most nearly resembles.

First. The combustion is not instantaneous, but takes place during an appreciable change in cylinder volume. All of the combustible material is not in the cylinder at the moment of ignition, as in the explosion engine, but is fed in and burned while the piston is moving. The heat is thereby generated at a more nearly constant temperature and does not reach the high temperatures or pressures of the explosion engine, which are generated practically instantaneously.

Second. Another peculiar feature of the manner in which this engine utilizes heat is the compression of the air for the combustion to such a degree that the heat developed thereby approximates the temperature obtained by the subsequent burning of the fuel.

This high elevation of temperature by compression is a necessary part of the improved method of using heat. It also causes the spontaneous ignition of the charge of fuel, although that is not the chief reason for the high compression. Such high compression is impossible in the explosion engine because the air, which also contains the full charge of combustible, would reach the ignition temperature too soon, and would produce a premature explosion. In the Diesel type of engines, however, the fuel is not introduced until the compression and heating of the air is completed. The high temperature of the compressed air, which is well above the ignition temperature of most fuels, makes it possible to dispense with any other ignition system, so that the engine in this respect is much simpler than the explosion engine. The necessity, however, of introducing the fuel into air that is under high pressure makes the introduction of fuel more difficult than in the explosion engine.

The cycle of operation of the Diesel engine, therefore, is to compress air to 450 to 500 pounds pressure per square inch, thereby generating a temperature of approximately 540° C. Into this highly heated air the fuel is injected during the return or second stroke of the engine, in a finely atomized form, at such a rate as will maintain an approximately constant temperature while burning and in such quantity as will yield the required work for that stroke. During the third stroke of the piston the expanded gases of combustion are pushed out of the cylinder, while a fourth stroke draws fresh air into the cylinder in preparation for a repetition of the cycle. This is the sequence of events in a four-cycle engine.

By supplying other means of freeing the cylinder from burned gases and refilling it with fresh air the necessary functions can be performed in two strokes of the piston, producing the so-called two-cycle engine.

In general appearance these engines are like explosion engines, although not built so heavily. They are provided with similar jacketing systems, cam-operated poppet valves, and heavy flywheels. They are usually built as single-acting vertical trunk engines, but are also made of the crosshead type, horizontal and double-acting.

In the four-cycle engines but one impulse is given to the piston in each two revolutions of the flywheel. In order to produce uniform angular velocity without excessively heavy flywheels, multiple cylinders are employed. There is also a practical limit to the size of any one cylinder, so that for large powers multiple cylinders are used at present almost to the exclusion of large single-cylinder engines, although further tests are being made of the practicability of the latter.

The Diesel engine has become a type of prime mover. It is based on certain principles, but is differentiated into many forms by different designers who seek various mechanical devices for reducing troubles and for more perfectly realizing the theoretical heat cycle developed by Diesel.

Among the mechanical difficulties giving rise to the great number of variations in design are those of introducing the fuel, scavenging the cylinder, and starting and reversing the engine.

The fuel is injected, atomized or sprayed, into the clearance space of the cylinder by air under a pressure sufficiently above that of the air compressed in this space. The air for injecting the fuel has to be under a pressure of about 700 or 800 pounds per square inch, and its reliable compression and storage form one of the mechanical difficulties of the engine.

In an attempt to avoid such high compression pressures and the resulting complications of design necessary in a true Diesel engine, the so-called "semi-Diesel" engine has been devised which does not compress the air charge sufficiently to raise its temperature to such a point that it will spontaneously ignite the injected fuel. Such engines depend upon projecting metallic parts within the head of the cylinder or upon external chambers communicating therewith that retain sufficient heat from the combustion of the previous charge to vaporize and ignite the fuel as injected. It is necessary to first heat such devices by some external source of heat in order to start the engine, but once the engine is running, the hot chamber insures spontaneous ignition. The fuel is introduced through similar fuel valves but requires less compression of air than is required in the true Diesel engine. Although such engines have theoretically a less efficient heat cycle than the true Diesel, they gain in simplicity of mechanism.

The scavenging of the cylinder performed by one stroke of the piston in the regular four-cycle engine is accomplished in some designs by blowing low-pressure air through the cylinder at the end of the exhaust stroke, this air being compressed either in the closed crank case or in an added cylinder.

To start Diesel engines, compressed air is stored in containers and let into the engine cylinders through separate starting valves.

References to the mechanical details and many facts of interest of the Diesel engines may be found in the journals mentioned under the bibliography reference numbers 25 to 130, and particularly in Der Oelmotor, a paper devoted to the mechanics of the oil motor, published in Berlin, Germany.

USE OF THE HEAVY-OIL ENGINE IN THE UNITED STATES.

Diesel developed his engine (131) in the early nineties, and has since then greatly improved it and has made of it a most successful and efficient power producer. At present it is thoroughly dependa-

ble and will burn a great variety of oils. But only within the past four or five years, however, has the engine been successfully constructed within the United States. Although the prime requisite in Europe seems to be economy in operation (132, 133), low first cost seems to be a more important requirement in this country, and at first comparison with the steam engine the Diesel seems to be exceedingly costly. Small imperfections in mechanical construction, up to within a very recent date, seem also to have had their influence upon the nonconstruction of the engine in the United States. Also, although the general industrial profits within the United States are large, the very abundance of raw materials and the general extravagance in their use seem to have combined against the wide adoption of this engine, in spite of its being so highly efficient and in spite of the fact that it has met with such success abroad.

Although the engines are reliable, lack of experience in handling engines with such high cylinder pressures has raised in some cases an undeserved prejudice against their use (134). Trouble in starting is usually due to unclean and ill-adjusted valves, and an auxiliary air supply is necessary. The exhaust valves become pitted and must be reground about every three months; but 15 minutes should suffice to replace a worn valve with a new one. Also, more lubricating oil is required than with a steam engine.

The wasteful practice of making coke in beehive ovens and the generally wasteful methods of steam raising in this country must give way to the more efficient methods of fuel utilization that now prevail in Europe, if the United States is to maintain its present position or compete with other countries in the manufacturing industries. With a more conservative use of the Nation's abundant fuel supplies and a better development of the by-product industries, there is no reason why the heavy-oil engine should not materially aid in the more efficient utilization of the fuel resources in the United States.

REQUIREMENTS OF A HEAVY-OIL ENGINE.

The features that are desirable in a heavy-oil engine (135) may be briefly set forth as follows:

1. The engine should primarily be constructed for burning heavy oils and residues, and particularly those oils containing asphlatums, such as the petroleums of the Pacific and Gulf coasts, because these oils are produced in large quantities and are the fuels now available in commercial quantities.
2. The engine should start without delay or trouble.
3. It should show reliability and general good-running qualities.
4. It should run equally well at full load and at no load, and with variable loads where speed variations are required.

5. It should run steadily enough to drive a dynamo for electric lighting.

6. It should burn the fuel completely and not give an unpleasant odor or smoke from the exhaust.

7. Its first cost should be low.

8. It should be simply constructed and should not require a machinist of superior ability to care for it.

SOME ADVANTAGES OF THE HEAVY-OIL ENGINE OVER THE STEAM AND THE EXPLOSION ENGINE FOR MARINE USE.

The advantages of the heavy-oil engine over the steam and the explosion engine for marine purposes are marked (136) and may be enumerated briefly as follows:

SMALLER PERSONNEL.

The heavy-oil engine requires less men than a steam engine of equal power. It is cleaner and much easier for the men to handle.

SAVING OF FIREROOM SPACE.

No fireroom is necessary. No stokers are required, and consequently there is no need of quarters for them.

SAVING OF BOILER SPACE.

The engine dispenses with boilers (137, 138). It requires no smokestacks—only a small exhaust stack—and no ventilating fans are necessary to the stokehole. It develops no smoke whatever. When the engine is running properly the exhaust is invisible.

SIMPLICITY OF HEAVY-OIL ENGINE.

The total weight of the engine is about the same as that of a reciprocating steam engine, not including the boilers and condensers. No igniter (139) or sparker is used; consequently there are no sparker troubles. There is no carbureter to get out of order. There is no trouble with preignition, as there is no fuel in the cylinder until it is injected at the desired instant. There is no violent initial pressure in the cylinders to cause an undue strain upon them, as there is in the explosion type of internal-combustion engine. No fresh water is required; salt water can be used for cooling the cylinders.

SAVING OF ENGINE-ROOM SPACE.

The engine room is 30 to 50 per cent smaller (140) than that of a steam engine of equal horsepower, and is more easily kept clean and in order.

ADVANTAGES OF OIL FUEL.

Admiral H. I. Cone, United States Navy, in a statement regarding the relative values of oil and coal for steam raising in the Navy, makes the following points (141) that so far as they go will also apply to the use of the internal-combustion engine:

The advantages of oil as compared with coal are:

An evaporation per pound of fuel in the ratio of about 14 to 9 (15.5 to 10) and per square foot of heating surface in about the ratio of 10 to 8 (12.5 to 10).

Fuel can be taken aboard more rapidly without manual labor and without interruption to the routine of the ship. The problem of fueling at sea is solved.

Steam for full power can be maintained as readily as for low power. A vessel burning oil is capable of runs at full speed limited in duration only by the supply of fuel. There is no reduction in speed due to dirty fires or to difficulty in trimming coal from remote bunkers or to exhaustion of the fireroom force.

There are no cinders and the amount of smoke can be controlled.

A considerable reduction in personnel is possible.

The weight and space required for boilers are reduced, first, by the reduction in heating surface required, and, second, by the shortening of firerooms. Consequent on the reduction in heating surface is a decrease in weight and cost of boilers.

Coal and ash handling gear is eliminated. This renders unnecessary the piercing of the hull for coal trunks and discharges from the ash expellers or ash ejectors.

The stowage and handling of oil are much easier than of coal and will result in a much cleaner ship, with consequent increase in time available for drills.

The mechanical supply of fuel to the boilers gives a prompt and delicate control of the steam supply, permitting more sudden changes in speed than with coal, which is a tactical advantage.

The nature of fuel oil permits utilization of remote portions of the ship and of constricted spaces for its stowage.

These advantages have long been recognized by the Navy, and there have been experiments with liquid fuel dating back as far as 1867. All these experiments have confirmed our belief in the considerable military advantages which will accrue from its use, but until recently it has been impracticable to use it extensively on account of the uncertainty as to the adequacy of its supply and the sufficiency of its distribution among the seaports of the world. We are now assured, however, as regards the supply, that there is sufficient oil on the public lands of the State of California alone to supply all probable naval demands for 100 years should oil be burned to the exclusion of coal, and of course there is considerable oil in other portions of United States territory (142). The question as to the distribution of oil among the ports from which fuel might be required by our vessels in time of war is one that is well within our power to solve, as from its nature the oil can be transported and stored more easily than can coal. Indeed for the transport of oil in time of war we are already better provided than for coal, there being a large number of tank steamers flying the American flag.

Oil is therefore certain rapidly to replace coal as a fuel for naval purposes.

ADVANTAGES IN STORAGE.

Furthermore, oil if stored in closed tanks, unlike coal (143–146), does not deteriorate on standing, nor is it subject to spontaneous combustion; but the greatest care should be given to its storage, as oil and its vapors are very searching and extreme precautions are advisable, though with proper ventilation of the tanks the danger

from fire is nil. Oil must be stored below the protective line in a war vessel, but should never be stored directly below the boilers.

Weight for weight, oil can be stored in a smaller space than coal. One ton or 2,000 pounds of bituminous steaming coal occupies approximately 40 cubic feet, according to A. H. Fay, mining engineer, Bureau of Mines, whereas a ton of oil occupies approximately 35 cubic feet. The relative storage value of coal as compared with oil is therefore 10 to 11.5.

A good steaming coal develops, according to A. C. Fieldner, chemist, Bureau of Mines, approximately 7,500 calories per gram. An average fuel oil develops approximately 10,500 calories. The relative calorific value, per unit weight, of coal as compared with oil is therefore approximately 10 to 14. For marine steam production, therefore, considering storage capacity, the relative value of coal to oil is 10 to 16.1, although the United States Navy gives a ratio even greater (158).

The relative efficiency of the steam engine compared with the heavy-oil internal-combustion engine (148–151) is conservatively 10 to 25. Or, for marine service, the ratio of the total power of a heavy-oil internal-combustion engine for marine propulsion to that of a coal steam engine, considering fuel storage, calorific value of fuel, and engine efficiency, is approximately 10 to 40.25.

VARIETY OF FUELS AVAILABLE.

The principal advantage of the engine over the gasoline, or explosion, engine is that it burns a great variety of these heavy oils, which are much cheaper and safer to carry than gasolines. Almost any liquid fuel that is fluid and is free from solid matter can be burned successfully in this engine.

FUEL AND MAINTENANCE COSTS OF HEAVY-OIL ENGINE.

Burning oils in a heavy-oil engine (152–156) instead of under boilers materially reduces the cost of fuel per unit of power developed, (see p. 14), while the maintenance costs are about the same.

FUEL ECONOMY OF HEAVY-OIL ENGINE.

The fuel economy of the heavy-oil engine may be briefly summarized as follows:

In a heavy-oil engine 200 to 250 grams, or approximately 0.4 pound, of oil is consumed in developing 1 horsepower-hour, whereas for a steam engine of the best triple-expansion type, from 1.1 to 1.8 pounds is necessary. This difference in fuel consumption gives an efficiency of the oil engine compared with the steamer of from 0.4 to 1.1 pounds, or a ratio of approximately 1 to 3 (157), or, conservatively, 10 to 25 in favor of the oil engine.

The efficiency of coal as compared with fuel oil for steaming is variously estimated at 10 to 17 (158), 10 to 15.5 (p. 12), and 10 to 16.1. (See p. 13.)

It may be of interest to note that a turbine engine taking steam from boilers fitted with the best Koerting burners for oil, with accessories complete, built by the Franco Tosi Co., Milan (159), and installed at the Turin Exposition in 1911, required two and one-half or more times the weight of oil fuel per horsepower than did a Diesel engine built and installed by the same company at the same time and place for purposes of direct comparison, thus giving a ratio of 25 to 10 in favor of the Diesel engine.

RELATIVE FUEL CONSUMPTION.

Per unit weight, not considering the relative storage capacities needed, the quantity of oil required for burning in an oil engine compares with the quantity of coal required for steam production as 35 to 10, as shown from the following statement:

Fuel economy.

Oil storage, 11.5, to coal storage, 10. (See p. 13.)
Calorific value of oil, 14, to calorific value of coal, 10. (See p. 13.)
Oil burned in an oil engine, 25, to oil burned for steam production, 10. (See p. 13.)

One gallon of water at 15° C. weighs 8.3316 pounds (160).

The average specific gravity of California crude oils is 0.9574 at 15° C. (See p. 18.)

One barrel (42 gallons) of California crude oil weighs, therefore, 335 pounds, and is equivalent to 1,172.5 pounds, or 0.58625 ton, of coal. From this ratio the cost of either fuel can be calculated from the market quotations (161).

The quantity of oil required in a heavy-oil engine and its resulting efficiency, estimated (162–166) within a margin of about 5 per cent, is approximately shown in the table following:

Fuel consumption and efficiency of a heavy-oil engine.

Load.	Pounds of oil per brake horse-power-hour.	Thermal efficiency (based on brake horse-power-hour).	Mechanical efficiency.
	Pound.	*Per cent.*	*Per cent.*
Full load	0.472	30	74
¾ load	.500	.....	65
½ load	.562	26	58
¼ load	.748	.....	47

When one considers that in good steam boiler and engine units the ordinary thermal efficiency is only 12 to 13 per cent, the advantage of the heavy-oil engine, for marine work particularly, is apparent.

The distribution of the total heating units from an oil when used in a Diesel engine is about as follows (167):

Heat balance of the Diesel engine.

	Per cent.
Total heating value of fuel	100.0
Indicated horsepower	44.2
Brake horsepower	32.7
Friction of air, water, and oil pumps	11.3
Cooling water	33.3
Exhaust gases	22.7

USES.

STATIONARY ENGINES.

The heavy-oil engine is being installed in a great variety of plants to produce power for many different uses. The stationary engines in use vary in size from 50 horsepower to large central-power installations, and they seem to run with perfect satisfaction (168–173).

MARINE ENGINES.

Since first constructed this engine has been developed to a remarkable degree for ship propulsion, and there are now several hundred ocean-going vessels being propelled by heavy-oil engines, ranging from small pleasure launches to vessels of 10,000 tons displacement, and larger ones are being continually built as the reliability and efficiency of the engine become better known (174–210).

Of particular note are the steamship *Selandia* (211–221), the steamship *Toiler* (222–226), and the steamship *Vulcanus* (227–228), each of which has successfully completed transoceanic voyages.

LOCOMOTIVES.

The next great development of the heavy-oil engine will probably be for locomotive use (229), and there is now building at the Sulzer Bros. works in Winterthur, Switzerland, a Diesel-engine locomotive to determine the practicability of the Diesel engine for locomotive propulsion.

The heavy-oil engine has already entered the field of land transportation in the propulsion of tram cars, and seems also to be successful there (230–236).

COMBUSTION OF THE FUEL.

DESIRABLE PROPERTIES OF FUEL.

In selecting a fuel for this engine its composition as affecting combustion is most important. For proper combustion (237) the fuel should be mobile and volatile, clean, and free from water, solid particles, and grit. In general the specific gravity of an oil rises directly as the vapor density. The boiling point and the amount of air necessary for combustion vary inversely with the volatility, and the greater the volatility of the fuel the better the ignition and combustion. The benzene-ring bodies [a] or benzol seem to be more difficult to break up than the paraffin-chain bodies, and the latter have a better diffusibility than the former. They are, therefore, more active and seem to give better results in combustion (238), though for this same reason they are more dangerous. The calorific value of bituminous tars in general is lower than that of lignite tars or petroleum products. Petroleum benzines require approximately 40 volumes of air, whereas the heavy petroleum products require approximately 100 volumes of air for complete combustion.

PETROLEUMS AND TAR OILS.

Petroleums, gas oils, and lignite tar oils (239) readily lend themselves to gasification and they leave practically no residue, giving them peculiar value in an oil engine. Anthracene and creosote oils gasify fairly well. Paraffin-chain bodies, in general, gasify very readily and are suitable for heavy-oil engines. Benzene-ring bodies however, volatilize more difficultly. They volatilize regularly and do not have the explosive tendency to be noted in the several kinds of petroleum products, which gives the latter the value peculiar to oil engines. An oil, to give best results in a heavy-oil engine, should on heating show a tendency to volatilize suddenly at some given temperature and not to give off vapors regularly and uniformly, that is, distil with the rise in temperature. To this tendency to sudden volatilization or explosion, in contradistinction to regular volatilization or uniform distillation, is due the value as a fuel in the heavy-oil engine (unlike the explosion engine fitted with carburetor and igniter where the time of combustion is so short).

Bituminous tar oil and tar itself are used in engines in which the fuel is ignited by sparks, glow points, hot retorts, or hot cylinder heads.

Lignite tar oils and bituminous tar oils mixed with 25 per cent anthracene give good results in a heavy-oil engine. In general, in a

[a] The benzene or closed ring bodies, known in organic chemistry also as the aromatic or carbocyclic series of hydrocarbons, described fully in the text-books (such as Richter's Organic Chemistry, vols. 1 and 2, 1900), comprise the benzenes of the coal tars and are distinctive from the paraffin or open chain bodies known in organic chemistry also as the alaphatic series of hydrocarbons, which comprises the paraffins of the petroleums.

good paraffin oil, the ratio of hydrogen to carbon, as shown by analysis, should be 10 to 15, and in bituminous tar oils the ratio should be about 10 to 12.5.

IGNITION.

If an oil be heavy, with a very low content of "flashy" constituents, it should be enlivened by having mixed with it before admission into the cylinder about 2 per cent of gaseous oil, such as the "gas oil" previously mentioned.

ALCOHOL VERSUS GASOLINE.

One gram of gasoline of specific gravity 0.71 to 0.73 requires approximately 15 grams of air for theoretically complete combustion, and under working conditions from 19 to 23 grams (240), whereas 1 gram of denatured ethyl alcohol, 90 per cent, requires theoretically 8 grams, and under working conditions from 9.5 grams to 11.5 grams. That is, under normal working conditions denatured alcohol requires about half the weight of air that gasoline requires; 25 to 50 per cent excess of air, however, is necessary in both cases for best results; or, stated in heat units, denatured alcohol, 94 per cent by volume, develops 5,833 calories per gram, whereas gasoline of specific gravity 0.71 to 0.73 develops 10,611 calories (240). Therefore the power developed by denatured alcohol and by gasoline is approximately 10 to 18 in favor of the gasoline. The difference in ignition temperature, a matter of prime importance in the Diesel engine, is also greatly in favor of the gasoline, because an explosive mixture of alcohol vapor and air can be compressed to over twice as high a pressure (180 pounds per square inch) as can an explosive mixture of gasoline vapor and air (70 pounds per square inch) before self-ignition takes place. Although explosion engines are hard to start with alcohol and are uncertain with variable loads, an explosion engine properly designed and regulated will run as well with alcohol as with gasoline; but less cooling water is required for the engine cylinders with alcohol than with gasoline.

USE OF WATER IN THE CYLINDER.

It is believed that an auxiliary nozzle could be advantageously used to inject a small quantity of water into the combustion cylinder simultaneously with the fuel. The nozzle must be removed as far as practicable from the fuel nozzle, however, so as not to dampen the ignition of the oil by the steam thereby generated. During ordinary running the cylinders are continuously superheated and must be cooled by water circulating externally. This circulating water cools the cylinder, carries away considerable heat, and thereby causes a

direct loss of fuel value. (See p. 15.) The water injected will generate steam or power by absorbing a portion of the surcharge of heat and converting it into power and will at the same time reduce, at least in part, the necessity for externally cooling the cylinders and thereby losing some heat. This principle has been practically developed by James Hargreaves (241) in his internal-combustion engines, and might be applied, so far as practicable, to eliminating the explosion pound of internal-combustion engines in general. That an engine so fed with water will run more quietly and smoothly has been demonstrated by Strong in his gasoline-alcohol tests (242). Even as low as 50 per cent alcohol and water has been burned by him in an explosion engine.

RELATIVE CALORIFIC VALUES OF SOME FUELS.

The calorific values (243–245) of the chemically pure fundamental bodies found in liquid fuels is given below for purposes of comparison:

Heat of combustion of pure liquids.

Substance.	Specific gravity.	Calories per gram.	Average. [a]
	0°. C		
Methyl (wood) alcohol, CH_3OH .....liquid..	[b] 0.810	5,307, 5,322 [c]	5,314
Ethyl (wine) alcohol, C_2H_5OH .....liquid..	[b] .791	7,184, 7,068, 7,082, 7,095 [d]	7,107
Hexane (paraffin), C_6H_{14} .....liquid..	[g] .677		[e] 11,603
Benzene, C_6H_6.....liquid..	[b] .899	9,978, 9,997, 10,025, 10,004 [f]	10,001
	15° C.		
Commercial gasoline [h]	.710–.730		11,368
Commercial kerosene [i]	.790–.800		11,050
Crude California asphaltic petroleums: [j, k]			
Coalinga (average of 53 samples)	.9462		10,501
Coalinga (average of 62 samples)	.9498		10,404
McKittrick (average of 26 samples)	.9566		10,282
Midway (average of 29 samples)	.9570		10,341
Kern (average of 40 samples)	.9645		10,307
Sunset (average of 25 samples)	.9701		10,266
Average of asphaltic petroleums	.9574		10,350

[a] The values given are with the water of combustion condensed to a liquid.
[b] Smithsonian physical tables, 1910, p. 90.
[c] Landolt, Börnstein, Roth, Phys. Chem. Tabellen, 1912, p. 913.
[d] Id., p. 913.
[e] Id., p. 909.
[f] Id., p. 910.
[g] Beilstein, Organische Chemie, vol. 1, 1901, p. 12.
[h] Average of nine analyses.
[i] Average of four analyses.
[j] Allen, I. C., Chemical and physical examination of the petroleums of the Coalinga (California) district: Bull. 398, U. S. Geol. Survey, 1910, pp. 267 and 269.
[k] Allen, I. C., and Jacobs, W. A., Physical and chemical properties of the petroleums of the San Joaquin Valley of California: Bureau of Mines Bull. 19, 1911, p. 26.

FUELS THAT CAN BE USED IN THE HEAVY-OIL ENGINE.

PETROLEUM PRODUCTS.

Many liquid fuels can be burned successfully in heavy-oil engines. Petroleum products of all kinds (246) from whatever source, from the lightest lamp oils to semifluid residues, have from time to time been successfully used.

Benzines of specific gravity 0.700 to 0.710 from Pennsylvania, of specific gravity 0.715 to 0.725 from India, and of specific gravity 0.745 to 0.755, and distilling between 140° to 160° C. from Roumania burn well, but are expensive (247–255).

Lamp oils and naphthas of specific gravity 0.850 to 0.950, distilling between 150° and 300° C., and of 10,300 to 10,800 calories, burn well but are also expensive.

"Solar oil" and "gas oil," specific gravity 0.800 to 0.930, distilling between 300° and 360° C., flash point 65° to 150° C., and generating 190 to 200 horsepower-hours per 10,000 calories, also burn well, are cheap, and are produced in considerable quantities.

Lima fuel oils, as Eagle oils, gas-oil tar distillates, and Austrian and Russian fuel-oil residues have a specific gravity of 0.943 to 0.952, a heating value of 10,500 calories, a viscosity of 3.6 Engler, and a flash point of 76° C.

Paraffin-oil residues have a specific gravity of 0.860 to 0.890 and a heating value of 9,750 calories.

Fuel-oil distillates from California and Texas have a specific gravity of 0.840 to 0.900 and a flash point of 60° to 100° C.

Asphaltum oils containing as high as 21 per cent asphaltum, according to a statement made to the author by W. R. Sands, of San Francisco, have been burned with success.

Mexican oils have a specific gravity of 0.878, a heating value of 10,000 calories, viscosity at 50° C., 1.64° Engler, and a flash point of 44° C.

"STEINKOHLE" OILS.

"Steinkohle" oils are heavy-oil distillates, having a specific gravity of 1.04.

Anthracene-oil distillates have a specific gravity of 1.1 and a heating value of 8,959 calories.

Tar-oil mixed distillates have a specific gravity of 1 to 1.1 and a heating value of 8,800 to 9,000 calories. These may be even so heavy that it is necessary to heat them in order that they may become fluid enough to flow.

BITUMINOUS OILS.

Bituminous oils (256–264) are from various forms of gas retorts, as inclined, rotary, vertical, and horizontal.

The vertical-oven tar oils have a specific gravity of 1.10 to 1.18, contain 0.2 to 4.3 per cent of free carbon, have a flash point between 40° and 71° C., and a viscosity of 1.8° to 45° Engler. This oil is mobile and has little free carbon.

The horizontal-oven tars have a specific gravity of 1.16 to 1.25, contain 14.9 to 33 per cent of free carbon, have a flash point between 71° and 90° C., and a viscosity of 16° to 51° Engler. Two gallons of tar oil develops approximately 29.7 indicated horsepower-hours.

These tars burn readily in heavy-oil engines, but on long running deposit some carbon in the cylinders. They should first be distilled and the crude distillate used, though if the tar be perfectly mobile complete combustion is readily obtained.

LIGNITE OILS.

The distillates of lignite oils are represented by light benzene of specific gravity 0.800 to 0.820, and solar oils of specific gravity 0.820 to 0.835, containing 13 to 14 per cent hydrogen. Benzene is successfully used in a sparking or explosion engine, because in this type of engine the time for volatilization and diffusion is greater than it is with a self-igniting heavy-oil engine. It has a tendency, however, to develop smoke. Light tar oils of specific gravity 0.845 to 0.870 and heavy tar oils of specific gravity 0.875 to 0.900, containing 11 to 13 per cent of hydrogen, have been burned successfully.

Paraffin-oil distillates have a specific gravity of 0.898 and a heating value of 9,790 to 9,836 calories.

Creosote-oil distillates have a specific gravity of 0.957 and a heating value of 9,880 calories.

TURF (PEAT) OILS.

Tar oils from the distillation of peat require more heat and time for volatilization than lignite tar oils, but an oil having a specific gravity as low even as 0.8533 has been successfully burned in a heavy-oil engine.

SHALE OILS.

The shale oils of Scotland of specific gravity 0.740 to 0.980 (265) have been used successfully.

VEGETABLE OILS.

Vegetable oils, as peanut oil of specific gravity 0.916 to 0.920 (266), cocoanut oil of specific gravity 0.925, castor oil of specific gravity 0.960 to 0.967, cottonseed oil of specific gravity 0.913 to 0.930, and palm oil of specific gravity 0.850 to 0.860 (267) have been burned satisfactorily in a heavy-oil engine, but are expensive and at present are not to be considered available, although in an emergency they could be used.

ANIMAL OILS.

Animal oils, such as lard oil, of specific gravity 0.913 to 0.919, like the vegetable oils, can be used successfully, but are high priced and only in an emergency are they to be considered as a fuel.

ALCOHOLS.

A mixture of 80 per cent alcohol and 20 per cent benzene (268) has been burned successfully in the heavy-oil engine. However, it has been found advisible to warm the engine by first starting it on a more volatile petroleum product, as benzine.

WOOD OILS.

Wood oils or creosote distillates of specific gravity 0.841 to 0.877 (269) have also been used to a limited extent with success.

In short, the following oils and mixtures of them have been used successfully in heavy-oil engines, provided they were mobile, free from free carbon, grit, and water, and were low in sulphur:

Petroleum products: Gasoline; lamp oils of all kinds; naphthas; gas oils; fuel-oil distillates; "masut" or residues from the crude oils of Russia; and crudes, if mobile.
"Steinkohle" oil products: Heavy oils; anthracene oils; and tar oils.
Bituminous oils: Retort oils of all kinds.
Lignite products: Benzene; solar oils; paraffin distillates; and creosote oils.
Turf oils: Creosote oils.
Shale oils.
Vegetable oils: Peanut oil; coconut oil; castor-bean oil; cottonseed oil; and palm-seed oil.
Animal oils.
Alcohols.
Wood oils: Creosotes.

TREATMENT OF HEAVY OILS TO MAKE THEM MOST SUITABLE FOR FUEL.

It has been stated in the previous pages that any fuel that will flow freely can be burned in a heavy-oil engine. Though this in a measure is true, heavy tarry oils, if not kept perfectly fluid by heating, will cool and tend to clog the pipes and valves. It is advisable, therefore, to first subject the tarry oils to a distillation (270), distilling over everything up to the tar residues or even to the cokes, and to use this distillate for fuel without further treatment. The cost of distillation will be outweighed by the more satisfactory running of the engine.

IGNITION OIL.

When the fuel oil is heavy and contains little volatile material, it is advisable to inject alongside the main fuel spray, by means of an auxiliary spray, a small quantity of an oil having a relatively low flash point, such as a heavy benzine or a "gas oil." This ignition

oil, igniting at the proper moment, will in turn ignite the more sluggish fuel oil, and proper ignition will thereby be insured. The ignition oil may also be injected within the fuel valve or first blended with the fuel itself in the storage tank.

Satisfactory ignition (271–272) has resulted from injecting the following quantities of an oil of low flash point into the immediate neighborhood of the fuel-oil spray:

Percentage of ignition oil compared to weight of fuel.

	Per cent.
At full load	1.5
At three-fourths load	6.9
At one-half load	12.7

SPECIFICATIONS FOR FUELS AND LUBRICANTS FOR HEAVY-OIL ENGINES.

FUELS.

The concensus of opinion seems to be (273–283) that an oil to burn with success in heavy-oil engines should possess the following characteristics:

SOLIDIFYING POINT.

The oil should be mobile at 0° C. If it be heavy or viscous or contain a considerable proportion of asphaltum or paraffin, it will become sluggish and stiff at low temperatures, and considerable heat will have to be used to warm it before it can be run into the engine.

FLUIDITY.

Sluggish oils should first be heated before being introduced into the engine. If it be necessary to use very heavy oils, the engine should first be warmed by running on a more fluid fuel and the heavy oil introduced only after the engine is hot and running well. This process should be reversed when shutting down, and the heavy oils should be washed out of the engine valves and pipes with a lighter oil, the engine being run a short time on one of these lighter oils before it is allowed to become cold.

TAR CONTENT.

An oil should contain not more than 0.4 per cent of material insoluble in xylene, as a larger proportion of insoluble material will tend to form coke in the cylinders. (Ten grams of the sample mixed with 10 cubic centimeters of xylene shaken and filtered should show not more than 0.04 gram increase on the filter.)

COKE RESIDUE.

The residue on coking should be not greater than 3 per cent. A high content of asphaltum or free-carbon will give considerable trouble by coking in the cylinders.

FREE-CARBON CONTENT.

There should be not more than a trace of free carbon in the oil, as free carbon tends to clog the valves and to deposit on the surfaces of the cylinders.

VOLATILITY.

At least 80 per cent of the oil should distill over at 350° C., for oil leaving more than 20 per cent residue at this temperature will show a large carbon content by coking.

DISTILLATION.

Heavy oils and residues, though they may be successfully burned in a heavy-oil engine, should properly be distilled (not refined) before using, as it is cheaper to prepare the oil before introducing into the engine than it is to dismantle the engine, or a part of it, for cleaning.

FLASH POINT.

The flash point should be between 60 and 100° C. (Abel-Pensky closed tester).[a] A small proportion of oil of a low flash point is required to insure ignition.

IGNITION OIL.

In general a heavy oil containing no material having a low flash point should be enlivened by the addition of about 2 per cent of a "gas oil," flash point 60 to 100° C. or less, before being fed into the cylinders.

SPECIFIC GRAVITY.

The specific gravity in itself, although of little significance, should be not greater than 0.920, because when greater the large proportion of heavy residual material would give trouble in the engine. In general the boiling point or distilling proportion is of more importance.

CALORIFIC VALUE.

The heating value should be not less than 9,000 calories, and the hydrogen content not less than 10 per cent, as lower values are approaching the value of pure carbon and will give poor combustion.

SULPHUR CONTENT.

The sulphur content should be not more than 0.75 per cent, as a greater proportion may attack the cylinder walls and will tend to

[a] The Abel-Pensky closed tester (see Holde D, Untersuchung der Mineralöle und Fette, Berlin, 1909, p. 52) provided with a water bath for oils flashing up to 60° C., and with an oil bath for oils flashing between 60° and 150° C., and a Pensky-Martens closed tester (see ibid., p. 133) for oils flashing above 150° C., are recommended for all flash tests. These instruments are the most widely known and used of any flash testers, are critically described in the literature, may be purchased from a number of makers, and although not perfect are more accurate than any other instruments so far constructed and most nearly show the true flash point of an oil. Modifications of these instruments are now under consideration by the Bureau of Mines in cooperation with a number of scientific societies.

pit them, making them rough. Brass, zinc, and copper are to be avoided in the surfaces exposed to combustion. Nickel steel seems to be the most resistant material.

ACID AND ALKALINE CONTENT.

The oil should contain no free ammonia, alkalies, or mineral acids, because of their pitting effect on the surfaces exposed to combustion.

ASH CONTENT.

The oil should contain not more than 0.05 per cent of noncombustible mineral matter, because such matter tends to hasten carbonization within the cylinders and to prevent proper combustion.

WATER CONTENT.

The water content should be not greater than 1 per cent. One per cent of water reduces the calorific value by 1 per cent. Moreover, to raise the temperature of 1 gram of water from room temperature, say 30°, to 100° C. requires 70 calories, and to evaporate 1 gram of water at 100° C. into steam at 100° C. requires 536 calories. Hence 1 gram of water causes a total reduction of 536 + 70, or 606 calories, and to raise the temperature of the steam to that of the cylinder requires still more heat. The absorption of heat in raising the temperature of the steam is partly compensated by the action of the steam in expanding and performing work on the piston, there being an abundance of heat in the cylinders (see pp. 17–18). In short, 1 per cent of water in the fuel itself will cause a loss of approximately 1.06 per cent in the calorific value of the fuel. It must also be remembered that a drop of water suddenly generated into steam within the fuel spray at the instant of ignition may lower its temperature and thereby prevent ignition, and a number of such drops in succession might stop the engine.

RESIN CONTENT.

The resin content should be low, as resins have a tendency to carbonize readily and will tend to coke in the cylinders.

CREOSOTE CONTENT.

Oils containing creosotes up to 12 per cent, though causing smoke to some extent, can be burned; a higher percentage of creosotes gives trouble by coking.

PARAFFIN CONTENT.

A paraffin content of 15 per cent will give some trouble. An oil containing a still higher percentage of paraffin, because of the large quantity of oxygen necessary for complete combustion, will burn with more difficulty.

ASPHALTUM CONTENT.

The heavy-oil engine, at least so far as the use of asphaltum oils is concerned, is still in its experimental stage, but the assumption can fairly be made that when the mechanical difficulties are surmounted it will be practicable to burn any fuel oil containing asphaltum that is sufficiently fluid to flow, providing the oil be free from solid matter and water. An oil containing 21 per cent asphaltum has been successfully burned (see p. 19).

ATOMIZATION.

Fine atomization is essential, for if the fuel enters the cylinder in drops of appreciable size, which can burn only from their surfaces, it will not have time for complete combustion. The fuel will consequently strike the sides of the cylinders and the piston head and there carbonize.

LUBRICANTS.

It is of importance to examine carefully the lubricating oils (284–287) for use in cylinders and pumps.

VISCOSITY.

The viscosity should be between 9° and 10° Engler [a] at 50° C. A lubricant of a much less viscosity would tend to burn and one of greater viscosity would tend to carbonize and would not lubricate so well.

SOLIDIFYING POINT.

The lubricant should be liquid at −5° C. and should not freeze solid above −10° C.

FLASH POINT.

The flash point should be between 220° to 240° C., Pensky-Martens closed tester.

CARBONIZATION.

When agitated with concentrated sulphuric acid the lubricant should lose not more than 10 per cent by carbonization. This sulphuric-acid test gives an indication of the quantity of unsaturated hydrocarbons present.

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[a] The Engler viscosimeter is the most widely known and used of any viscosimeter now available for oil testing. Its parts and method of manipulation are critically described in the literature, and tables of values for comparing its readings with similar instruments have been prepared. (See Gray, T. T., A comparison of the Engler and Saybolt viscosities of mixed oils. 8th Int. Cong. Appl. Chem., vol. 10, 1912, pp. 153–158; Meissner, Walther, Vergleichende Untersuchungen über den Engler'schen, Redwood'schen und Saybolt'schen Zähigkeitsmesser. Chem. Rev. Fett-Harz-Ind., vol. 19, February, 1912, pp. 30–33, and March, pp. 44–49. Ubbelohde, L., Einige Neuerungen am Engler'schen Schmieröl-Viskosimeter und Tabellen für das Viskosimeter. Chem. Zeit., vol. 31, 1907, p. 1099.)

This type of instrument, however, does not give the true viscosity or lubricating value of an oil.

There is now being constructed by the Bureau of Mines a new viscosimeter that, it is believed, will show material advantages over this and other types of instruments now available, and will more nearly show the true lubricating value desired.

SOLUBILITY.

The lubricant should dissolve completely and clearly in benzene.

ACIDITY.

The lubricant should be free from acids and alkalies, as these pit the metal surfaces, and free from resins and fats, as these saponify readily.

ANIMAL AND VEGETABLE OILS.

Because of their tendency to decompose, animal and vegetable oils should not be used (288).

CONCLUSION.

The heavy-oil engine can not yet be considered as fully developed and much work remains to be done in perfecting it. With the present imperfect knowledge of what the engine is capable of doing, and of what particular oils can be successfully used in it, one can not speak conclusively as to definite specifications for fuels and for lubricants, and those outlined above must be considered, therefore, as tentative.

But the fact that petroleums containing as high as 20 per cent asphaltum as well as oils from tars have been successfully used is most encouraging. The future of the engine, and also a more efficient utilization for asphaltum liquid fuels and coal and wood by-product liquid fuels is assured.

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